LIFE 11 - Operation CO_2

Analysis of the carbon uptake capacity of the Scots pine (*Pinus sylvestris* L.) forests in the La Muntanya d'Alinyà Mountains under several climate and management regimes.

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Introduction:

Here we try to evaluate the suitability of several Scots pine (*Pinus sylvestris* L.) plots located in La Muntanya d'Alinyà Mountains (Lleida, Catalunya, Spain) as a **sink of carbon during the next 86 years** (until 2100) under different climate change scenarios and management regimes. This report is part of the commitment between the **GOTILWA+ team** and the **Catalunya-La Pedrera Foundation**, in the frame of the EU project LIFE **"Operation CO_2" (LIFE11 ENV/ES/535 Operation CO_2, Action B1 (development of Forest and Carbon management programme for Area A)**.

Human induced (IPCC, 2013) climate change is predicted to be the most affecting factor to the socio-economic and political environmental issues all over the European Union (EU) in the 21th century (Schröter *et al*, 2005; Holman *et al*, 2008). It is crucial to

understand and to anticipate the impacts of climate change upon both ecosystems and human society, and act proactively and appropriately upon them (Vitousek, 1994). All the knowledge acquired during last decades in how climate change is going to affect ecosystems and by extension, society, must crystallize in useful managing tools for stakeholders to allow them to mitigate the projected negative impacts of global change over Earth ecosystems (Folke *et al*., 2004). Those tools should have to be hardy enough to deal with the uncertainty associated to future climate conditions. Moreover, those tools should be easily available for managers and policy makers. In this direction pointed out the EU white document (European Union, 2009). Thus, the need of easily available, non-scientific friendly, robust mitigation management strategies has been highlighted to help stakeholders and policy makers to implement the right policies and practices to deal with climate change (Biesbroek *et al.*, 2010).

Forest ecosystems offer a wide range of products and services that are crucial for society (Millennium Ecosystem Assessment, 2003; Mavsar, 2010). One of them is the atmospheric CO_2 uptake capability (Pan *et al.*, 2011). Its capacity may be increased with proper management practices (Vayreda *et al.*, 2012), in particular in environments where water resources are limiting for tree growth and forest fires are frequent, as in Mediterranean environments (Palahí *et al.*, 2008). Furthermore, appropriated forest management practices increases the resilience of forest communities to climate change both by reducing the competition between stems for water (Cotillas *et al.*, 2009) and promoting a forest structure less vulnerable to abiotic disturbances, such as forest fires or strong wind events (Gardiner and Quine, 2000).

In this report we analyze the response of three Scots pine's (*Pinus sylvestris* L.) forest stands to three management regimes under several climate change scenarios to evaluate their carbon sink capacity.

Materials and Methods:

Simulation model:

We used the process-based forest simulation model GOTILWA+ (Growth Of Trees Is Limited by WAter, www.creaf.uab.es/gotilwa) (Nadal-Sala *et al*., 2014) to evaluate the evolution of three Scots pine forest stands located in the La Muntanya d'Alinyà Mountains. We simulated the forests stands under three management regimes and under three different climate change scenarios.

Stand characteristics:

Forest stand characteristics considered were the ones provided by the Catalunya-La Pedrera Foundation to the GOTILWA+ team. Tree density values for each forest stand are shown in table 1. Forest inventories were performed during July 2013.

Table 1: Tree density per plot. All values are given in trees·ha^{-1}.

	Diametric class								
Plot	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40+	Total
Plot 1	221	123	147	147	221	123	49	25	1054
Plot 2	309	309	476	619	238	0	24	48	2024
Plot 3	371	74	124	124	0	124	74	49	939

Slope is crucial to determine the hydrological traits of the stand. It was also provided by the Catalunya-La Pedrera Foundation. For **plot 1** the slope considered was **48 º**, for the **plot 2** the slope considered was **44 º**, and for **plot 3** the slope considered was **50 º**.

Soil characteristics are a key point to correctly model forest growth, because soil water holding capacity is closely related to tree water availability (Pastor and Post, 1986), and tree growth is closely related to water availability. Soil water holding capacity depends on the soil depth and its amount of organic matter. Following Olarieta *et al*. (2004, page 82), we assumed a **soil depth of 60 cm**. The amount of carbon present in **organic**

horizons (L+F) was defined as **20 tC·ha^{-1}**. The fraction of carbon in the mineral horizons **(A+B)** considered was **6%** of dry weight. **Stoniness of the soil** was fixed at **30%** of the soil volume.

Meteorological data:

Meteorological data have been obtained by disaggregating the monthly data given by Niñerola *et al*., (2007a, b) of **precipitation, mean maximum and minimum temperature, and solar radiation** in a 1x1 km^2 pixel grid centered in the **1.44ºE 42.16ºN coordinates.** They are focused in the La Muntanya d'Alinyà Mountains. Those data covers the 1951-2100 period. As **GOTILWA+ needs daily values to run**, which are not available in the original meteorological series, monthly values needed to be disaggregated into daily values. Here, a 15-years meteorological reference time-series was used to obtain the daily temporal autocorrelation for the meteorological data. **Meteorological reference time-series used was the MeteoCAT station of Montesquiu**. It is located at 2.24ºE 42.11ºN. Daily meteorological values of the **Reference Meteorological Series (RMS)** were obtained by applying an algorithm based on the Markovian transition probability matrix. It assigns the **temporal autocorrelation calculated in the Montesquiu meteorological series to the monthly data of the La Muntanya d'Alinyà pixel**, and gives as a result **daily values** of **precipitation, maximum and minimum temperature, and solar radiation.**

After disaggregating the monthly meteorological values to the daily meteorological values of the RMS, another autocorrelation analyze was run to obtain the real values for the La Muntanya d'Alinyà Mountains and project them to the future. Here the **assumption that variability in the future climate would be the same observed in the original time-series** was necessarily made. This assumption is necessary because no

climate-variability projection was available for the La Muntanya d'Alinyà Mountains. In this step, a **86 years long daily meteorological time-series was obtained**, so called the **Baseline Meteorological Time-series (BMT)**, from year 2015 to year 2100.

BTM has been modified according to three climate change scenarios, being the **RCP0.0 the 0 emissions** scenario, the **RCP2.6 the moderate climate change scenario** and the **RCP8.5 the extreme climate change scenario**. They are listed in table 2:

Table 2: Climate change scenarios applied to the BTM meteorological series. All climate change scenarios are based on the IPCC (2013).

Climate change scenario	Annual CO_2 increment (ppm·any^{-1})	Yearly anomaly in temperature (º·year^{-1})	Yearly anomaly in precipitation (%·any^{-1})
RCP0.0	0	0	0
RCP2.6	0.21	0.019	-0.2
RCP8.5	5.5	0.059	-0.33

For the **BTM + RCP0.0** scenario, mean yearly precipitation was **886 mm·year^{-1}**. Fort the **BTM + RCP2.6** scenario, mean yearly precipitation was **807 mm·year^{-1}**. For the **BTM + RCP8.5** scenario, mean yearly precipitation was **752 mm·year^{-1}**.

Mean annual temperature was: 8.3 ºC for the BTM + RCP0.0; 9.1 ºC for the BTM + RCP2.6 and 10.7 ºC for the BTM + RCP8.5.

Management regimes:

Management regimes were adapted from the original management plan (Fundació Territori i Paisatge, 2003) and from the ORGEST Scots pine management regimes (Piqué *et al*., 2011). A simulation under no forest management regime was already run for each plot to obtain a baseline to compare the de carbon storage capacity gain in each management. All management actions were projected to be performed during the dormant period – day 364 of simulation –.

ORGEST forest management procedures were selected based on the following criteria:

- Quality of the plots has been established in **quality A under ORGEST criteria**.
- **Low fire risk** was expected for all three plots.
- We chosen **the best evenaged** and **the best unevenaged** forest management procedures in wood production in order to **maximize the CO_2 sequestration**.
- **Final cut** has long enough to be projected to **year 2100**.

The two ORGEST management procedures selected were **Ps02** (Table 3, evenaged), and **Ps05** (unevenaged).

Table 3: Adaptation of the ORGEST management procedure Ps02 to the La Muntanya d'Alinyà plots. The final density is the stem density remaining in the plot (in trees·ha^{-1}) after management intervention is done.

Year	Type of thinning	Final density (trees·ha^{-1})	Number of removed trees (trees·ha^{-1})
2015	Small trees	800	Initial density dependent
2037	Small trees	450	350
2061	Small trees	200	250
2087	Several DBH classes	100	100
2100	Final cut	0	100

Ps05 management has a **rotation period of 10 years**, **starting in year 2015**. Actuations on forest population are focused in extracting **bigger trees (table 4)**. Regeneration has been fixed as **450 trees/ha** after each rotation period. Remaining density after interventions has been set to **1026 trees·ha^{-1}**.

Table 4: Adaptation of the ORGEST management procedure Ps05 to the La Muntanya d'Alinyà plots. The final density is the stem density remaining in the plot (in trees·ha^{-1}) after management interventions are done. Regeneration (in trees·ha^{-1}) is the number of saplings allowed to survive after each intervention.

Initial year (year)	Rotation period (years)	Type of thinning	Final density (trees·ha^{-1})	Regeneration (0-5 cm diameter) (trees·ha^{-1})
2015	10	Bigger trees	1026	450

From the two possibilities of management presented in the **original management plan (OMP)** (Fundació Territori i Paisatge, 2003), which were one unevenaged and one evenaged management procedures, **a unevenaged criteria has been chosen following section 5.1**. This section suggests that management regimes in Scots pine plots in the La Muntanya d'Alinyà mountains have to be focused in maintaining the irregular structure of the forest in order to guarantee the stability of the ecosystems currently present in the zone and to facilitate a vertical and horizontal tree population structure heterogeneity which increases the ecological niches for the non-tree species (Fundació Territori i Paisatge, 2003; page 10).

OMP management has a **rotation period of 12 years**, **starting in year 2015**. Actuations on forest population are focused in extracting **bigger trees (table 5)**. Regeneration has been considered as **450 trees/ha** after each rotation period. Remaining density after interventions has been set to **800 trees·ha^{-1}**.

Table 5: Adaptation of the Original Management Plan (OMP) to the La Muntanya d'Alinyà plots. The final density is the stem density remaining in the plot (in trees·ha^{-1}) after management interventions are done. Regeneration (in trees·ha^{-1}) is the number of saplings allowed to survive after each intervention.

Initial year (year)	Rotation period (years)	Type of thinning	Final density (trees·ha^{-1})	Regeneration (0-5 cm diameter) (trees·ha^{-1})
2015	12	Bigger trees	800	450

All simulations present a **rotation length of 86 years**, and **finishes at year 2100**.

Determination of Carbon stocks:

Carbon stocks in the plots have been determined using the **Verified Carbon Standard** methodology for the improved forest management: conversion of low productive to high productive forest (Face the future, 2013). Selected carbon pools were the

aboveground biomass, the **belowground biomass** and the **carbon fixed in wood products**.

Biomass to carbon transformation has been set as **0.5 gC·g^{-1}**. **Wood density** has been set as **0.47 g·cm^{-3}** according to IEFC (Gracia *et al*., 2004).

A conservative point of view was applied in dead wood and it has been considered as **non carbon pools in all cases**. Furthermore, soil carbon stock has been considered in equilibrium during the simulations. As a conservative point of view, its balances are not included in our results as indicates Face the future (2013).

No leakage is considered in this analysis.

Annual changes in carbon stock (ΔCs) were determined following Eq 1:

Eq. 1] $$\Delta Cs_t = \left(\frac{\Delta ABM_t + \Delta BBM_t}{Fc} + \frac{\Delta YLD_t * \rho}{Fc} \right) * \frac{44}{12}$$

Where ΔCs_t is the increment in carbon storage at year t in $tCO_2e \cdot ha^{-1} \cdot year^{-1}$, ΔABM_t is the increment in aboveground biomass at year t, in $t \cdot ha^{-1} \cdot year^{-1}$, ΔBBM_t is the increment in belowground biomass at year t, in $t \cdot ha^{-1} \cdot year^{-1}$, ΔYLD_t is the increment in wood volume extracted at year t, in $m^3 \cdot ha^{-1} \cdot year^{-1}$, Fc is the fraction of carbon in the biomass, in $tC \cdot t^{-1}$, and ρ is the wood density in $g \cdot cm^{-3}$.

Cumulated carbon stock (Cs_t) was defined, then, following Eq. 2:

Eq. 2] $$Cs_t = Cs_{(t-1)} + \Delta Cs_t$$

Where Cs_t is the cumulated stock at time t, in $tCO_2e \cdot ha^{-1}$, Cs_t is the cumulated stock at time t - 1, in $tCO_2e \cdot ha^{-1}$, and ΔCs_t is the increment in carbon storage at year t in

$tCO_2e \cdot ha^{-1} \cdot year^{-1}$. The sum of the Cs_t from year 1 to a given year is the total carbon stock (Cs).

A total greenhouse gas emission reduction for each management procedure (ΔC_{WPS}) and for the baseline (ΔC_{BSL}) is obtained at the end of the **86 years rotation length**. The difference between ΔC_{WPS} - ΔC_{BSL} is the net gain in emission reduction for a given management procedure (ΔC_{IFM}), in the equation 3:

$$\text{Eq. 3]} \qquad \Delta C_{IFM} = \Delta C_{WPS} - \Delta C_{BSL}$$

ΔC_{BSL} is obtained following equation 4:

$$\text{Eq. 4]} \quad \Delta C_{BSL} = \sum_{t=1}^{RL} \Delta Cs_{BSL,t}$$

Where ΔC_{BSL} is the greenhouse gas emission reduction for the baseline in $tCO_2e \cdot ha^{-1}$ at the end of the rotation length, RL is the rotation length, in years, t is the year, and $\Delta Cs_{BSL,t}$ is the increment in carbon storage at year t, in $tCO_2e \cdot ha^{-1} \cdot year^{-1}$.

ΔC_{WPS} is obtained following equation 5:

$$\text{Eq. 5]} \quad \Delta C_{WPS} = \sum_{t=1}^{RL} \Delta Cs_{WPS,t}$$

Where ΔC_{WPS} is the greenhouse gas emission reduction for a given management procedure in $tCO_2e \cdot ha^{-1}$ at the end of the rotation length; RL is the rotation length, in years, t is the year, and $\Delta Cs_{WPS,t}$ is the increment in carbon storage at year t, in $tCO_2e \cdot ha^{-1} \cdot year^{-1}$.

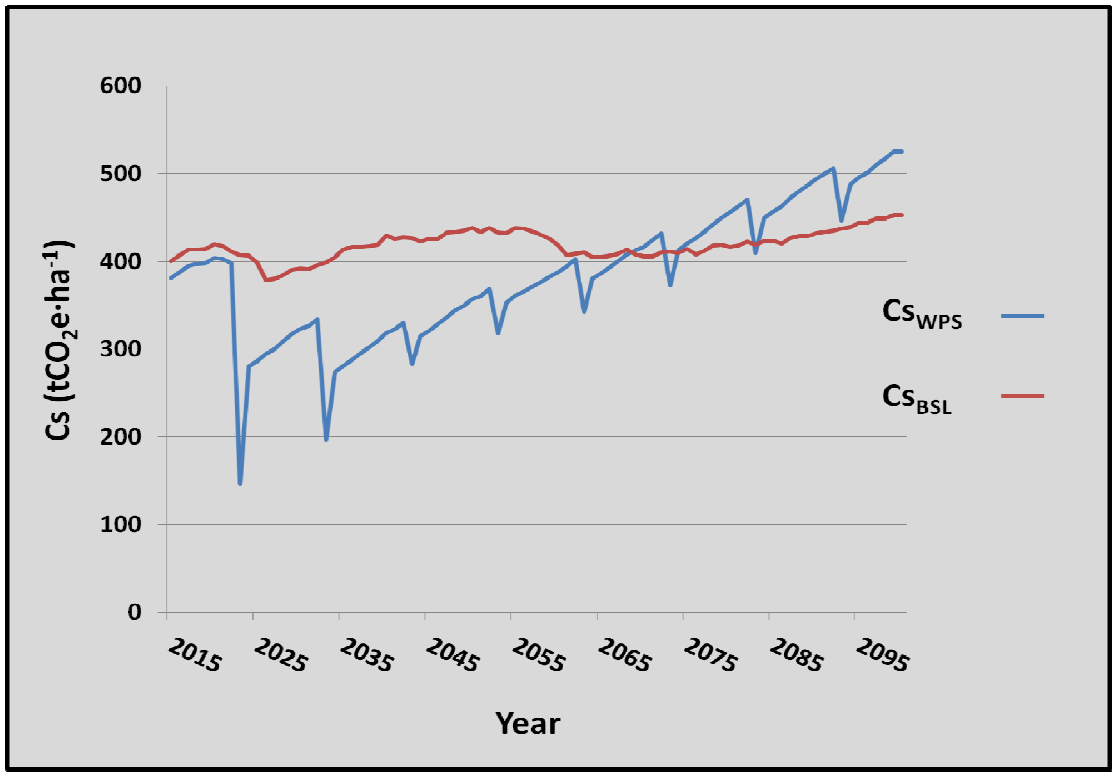


Figure 1: *Example of comparison between the carbon stock in the baseline (Cs_{BSL}), in red, and the carbon stock in a given management procedure (Cs_{WPS}), in blue.*

Wood quality:

Two wood quality categories has been considered following Llotja de Contractació i Mercat en Origen de Vic (2014), according to the **commercial value** of the wood extraction. **Medium** wood quality is **between 14 cm and 35 cm mean diameter**, and **high** wood quality is **more than 35 cm mean diameter**.

Results:

Plot 1:

Table P1.1: Total carbon cumulated stock (Cs, in $tCO_2e \cdot ha^{-1}$) in plot 1 at year 2100 horizon. The different RCP scenarios are noted for each management regime, with the baseline and the No Management regime.

Management	RCP 0.0 Cs ($tCO_2e \cdot ha^{-1}$)	RCP 2.6 Cs ($tCO_2e \cdot ha^{-1}$)	RCP 8.5 Cs ($tCO_2e \cdot ha^{-1}$)
Ps02	317.9	307	424.58
Ps05	525.6	524	720.9
OMP	486.3	489.1	670
No Management	453.1	391.7	555.1

In Table P1.1 are shown the total carbon cumulated stock (Cs) values in plot 1 for each climate scenario and for each management regime option. There is an **increase of about ~30%** of Cs in the **RCP 8.5** climate change scenario compared to the RCP 0.0 climate scenario. This increment can be explained both by a fertilizing effect upon production of an increase in atmospheric CO_2 concentration (Keenan *et al.*, 2011; Keenan *et al.*, 2013); and by an increase in temperature, enlarging the growing period of the Scots pine and increasing the energy available for the photosynthetic processes. In the **RCP 2.6 there is a slight reduction** in Cs due a moderate increase in aridity and a minor increase in atmospheric CO_2, with no remarkable fertilizing effect. In all climate scenarios the management regime with a **greater Cs is the Ps05**. Conversely, in all climate scenarios **Ps02 present lower Cs values** than the No Management baseline.

Table P1.2: Total carbon stock gain (ΔC_s, in $tCO_2e \cdot ha^{-1}$) in plot 1 during the 2015-2100 period. The different RCP scenarios are noted for each management regime, with the baseline and the No Management regime.

Management	RCP 0.0 ΔCs ($tCO_2e \cdot ha^{-1}$)	RCP 2.6 ΔCs ($tCO_2e \cdot ha^{-1}$)	RCP 8.5 ΔCs ($tCO_2e \cdot ha^{-1}$)
Ps02	-78	-89.5	27.4
Ps05	144.6	143.4	339.2
OMP	131.9	134.7	314.9
No Management	52.4	-9	153.8

Total carbon stock gain (ΔC_s) is higher in each simulation in the RCP 8.5 scenario (Table P1.2). It is noticeable that in **Ps02 management regime**, values in the RCP 0.0 and RCP 2.6 are negative, indicating **net CO_2 release** from the forest at the end of the simulation. It is also noticeable that for **the two unevenaged managements** (Ps05 and OMP) values are much higher than in the No Management scenario, indicating a higher sink suitability if a correct management procedure is applied.

However, as is shown in table P1.3, in the unevenaged management regimes wood quality is lower than in evenaged management regime. In those management regimes trees are not capable to grow as higher as in the evenaged stand. Thus, economic revenue, is going to be lower per wood unit in unevenaged management regimes. In addition, carbon residence time is higher in high quality wood products.

Table P1.3: Annual profitable wood extraction in $m^3 \cdot ha^{-1} \cdot year^{-1}$ for each management regime and for each climate change scenario. Wood quality has been differentiated between medium quality wood (14-35 cm) and high quality wood (35+ cm).

Management	Wood quality	RCP 0.0 ($m^3 \cdot ha^{-1} \cdot year^{-1}$)	RCP 2.6 ($m^3 \cdot ha^{-1} \cdot year^{-1}$)	RCP 8.5 ($m^3 \cdot ha^{-1} \cdot year^{-1}$)
Ps02	Medium (14-35 cm)	1.7	1.7	0.7
	High (35+ cm)	3.5	3.4	5
Ps05	Medium (14-35 cm)	5.5	5.5	7.2
	High (35+ cm)	0	0	0
OMP	Medium (14-35 cm)	5.7	5.7	7.6
	High (35+ cm)	0	0	0
No management	Medium (14-35 cm)	0	0	0
	High (35+ cm)	0	0	0

Ps05 is the forest management procedure that better improves the greenhouse gas emission reduction compared to the baseline (ΔC_{IFM}) of the plot 1 (table P1.4). Its values range between **72.5-165.8 $tCO_2e \cdot ha^{-1}$**. The **least efficient one is the Ps02**, with values ranging from **–135.2 to –84.7 $tCO_2e \cdot ha^{-1}$**. Thought, Ps02 has a lesser capacity of CO_2 sink than the no management option in all the climate change scenarios. In the case

of the **OMP** management procedure, values range from **33.3 to 114.9 $tCO_2e \cdot ha^{-1}$** depending on the climate change scenario considered.

Table P1.4: Greenhouse gas emissions reduction compared to the baseline (ΔC_{IFM}, in $tCO_2e \cdot ha^{-1}$) of the plot 1 for each management procedures and climate change scenarios.

Management	RCP 0.0 ΔC_{IFM} ($tCO_2e \cdot ha^{-1}$)	RCP 2.6 ΔC_{IFM} ($tCO_2e \cdot ha^{-1}$)	RCP 8.5 ΔC_{IFM} ($tCO_2e \cdot ha^{-1}$)
Ps02	-135.2	-84.7	-130.5
Ps05	72.5	132.6	165.8
OMP	33.3	97.4	114.9

Forests are crucial in the water quality and quantity of the water available for the society (Neary *et al.*, 2009). Thus, forest hydrological cycles modification is increasing in importance in current forest management plans. It is especially true under the drier conditions projected by climate change in the south-western Mediterranean basin. The analysis shows an exciting trend in the transpiration of the forest analyzed (Table P1.5). In a non managed forest stand, water is in equilibrium with the water availability – i.e. decreases in water availability are translated to decreases on tree transpiration -. However, under all management regimes which decrease the intra-specific competition between tree stems, water is not the limiting resource but energy. At increasing temperature – and, thus, energy available – forest stand increases its transpiration, conversely to the non-managed forest, which is more limited by intra-specific competition. It is observed for all climate change scenarios.

Table P1.5: Yearly transpiration (Ec, in $mm.year^{-1}$) of the tree population for each management procedure and climate change scenario. Baseline no management procedure is already noted.

Management	RCP 0.0 Ec ($mm \cdot year^{-1}$)	RCP 2.6 Ec ($mm \cdot year^{-1}$)	RCP 8.5 Ec ($mm \cdot year^{-1}$)
Ps02	318	318	325
Ps05	278	283	290
OMP	262	270	280
No Management	356	353	349

Plot 2:

Table P2.1: Total carbon cumulated stock (Cs, in $tCO_2e \cdot ha^{-1}$) in plot 2 at year 2100 horizon. The different RCP scenarios are noted for each management regime, with the baseline and the No Management regime.

Management	RCP 0.0 Cs ($tCO_2e \cdot ha^{-1}$)	RCP 2.6 Cs ($tCO_2e \cdot ha^{-1}$)	RCP 8.5 Cs ($tCO_2e \cdot ha^{-1}$)
Ps02	432.5	426.8	538.9
Ps05	616.2	615.2	811.1
OMP	575.3	577.9	757.1
No Management	573.5	493.5	648

The forest management procedure that **maximizes in all cases the Cs is the Ps05**, with values ranging from **615.2 to 811.1 $tCO_2e \cdot ha^{-1}$** depending on the climate scenario (table P2.1). In general terms, **RCP 2.6** is the climate scenario that supports lowest values of Cs in the plot for all management procedures. On the other hand, **RCP 8.5**, as mentioned above, is the climate scenario that presents higher Cs values. The **evenaged (Ps02)** management procedure is the management procedure with lowest Cs values in all climate scenarios, even **lower values than no management option**.

Table P2.2: Total carbon stock gain (ΔC_s, in $tCO_2e \cdot ha^{-1}$) in plot 2 during the 2015-2100 period. The different RCP scenarios are noted for each management regime, with the baseline and the No Management regime.

Management	RCP 0.0 ΔCs ($tCO_2e \cdot ha^{-1}$)	RCP 2.6 ΔCs ($tCO_2e \cdot ha^{-1}$)	RCP 8.5 ΔCs ($tCO_2e \cdot ha^{-1}$)
Ps02	-26.6	-32.3	79.4
Ps05	285.9	284.8	480.8
OMP	193.9	196.5	375.6
No Management	38.4	-41.4	112.2

As in the Cs case, the **forest management with greatest values of ΔC_s during years 2015-2100 is the Ps05** (Table P2.2). Furthermore, it is true for all climate change scenarios. **Lowest values of ΔC_s are found in the Ps02 evenaged forest management procedure**. In the RCP 0.0 and RCP 2.6 those values are negative, indicating net CO_2

release to the atmosphere at the end of the management procedure. However, in a RCP 8.5 climate change scenario, even under the forest management procedure Ps02 plot 2 becomes a sink of carbon, with a ΔC_s value of 79.4 $tCO_2e \cdot ha^{-1}$. Considering climate change scenarios, **the climate change scenario that presents higher ΔC_s values is the RCP 8.5 for each management**, even in no management procedure.

Table P2.3: Annual profitable wood extraction in $m^3 \cdot ha^{-1} \cdot year^{-1}$ for each management regime and for each climate change scenario. Wood quality has been differentiated between medium quality wood (14-35 cm) and high quality wood (35+ cm).

Management	Wood quality	RCP 0.0 ($m^3 \cdot ha^{-1} \cdot year^{-1}$)	RCP 2.6 ($m^3 \cdot ha^{-1} \cdot year^{-1}$)	RCP 8.5 ($m^3 \cdot ha^{-1} \cdot year^{-1}$)
Ps02	Medium (14-35 cm)	3.2	3.2	2.1
	High (35+ cm)	2.6	2.5	5.1
Ps05	Medium (14-35 cm)	6.7	6.8	8.4
	High (35+ cm)	0	0	0
OMP	Medium (14-35 cm)	6.9	6.9	8.7
	High (35+ cm)	0	0	0
No management	Medium (14-35 cm)	0	0	0
	High (35+ cm)	0	0	0

The only forest management procedure that allows obtaining high quality wood is the Ps02 (Table P2.3). However, the total amount of extracted wood is lesser than the other two forest management scenarios. The RCP 8.5 is the climate scenario that produces the largest amount of extractable wood for all forest management procedures. Conversely, RCP 0.0 is the climate scenario that produces the minor amount of both high and medium quality wood.

Table P2.4: Greenhouse gas emissions reduction compared to the baseline no management procedure (ΔC_{IFM}, in $tCO_2e \cdot ha^{-1}$) of the plot 2 for each management procedures and climate change scenarios.

Management	RCP 0.0 ΔC_{IFM} ($tCO_2e \cdot ha^{-1}$)	RCP 2.6 ΔC_{IFM} ($tCO_2e \cdot ha^{-1}$)	RCP 8.5 ΔC_{IFM} ($tCO_2e \cdot ha^{-1}$)
Ps02	-141	-66.7	-109
Ps05	42.7	121.7	163.1
OMP	1.8	84.4	109.2

The greenhouse gas emissions reduction compared to the baseline no management procedure (ΔC_{IFM}) takes **negative values for the Ps02 forest management procedure under all climate conditions** (Table P2.4). It indicates lower sink capacity of the forest compared to the baseline. Conversely, **Ps05 has a net positive ΔC_{IFM} that ranges between 42.7-163.1 $tCO_2e \cdot ha^{-1}$** depending on the climate change scenario considered. **OMP** presents lower but positive values (**1.8-109 $tCO_2e \cdot ha^{-1}$** depending on the forest management considered). Except for Ps02 forest management procedure, the highest ΔC_{IFM} values are obtained in **RCP 8.5** climate scenario.

Table P2.5: Yearly transpiration (Ec, in $mm.year^{-1}$) of the tree population for each management procedure and climate change scenario. Baseline no management procedure is already noted.

Management	RCP 0.0 Ec ($mm \cdot year^{-1}$)	RCP 2.6 Ec ($mm \cdot year^{-1}$)	RCP 8.5 Ec ($mm \cdot year^{-1}$)
Ps02	296	299	309
Ps05	265	270	278
OMP	256	263	274
No Management	360	356	351

In a no managed forest, tree transpiration (Ec) decreases at increasing aridity (Table P2.5). On the other hand, tree transpiration increases at increasing severity of climate change in any forest management procedure. However, Ec values in the plots under forest management do not reach No Management Ec values in any case. It means that management in all cases reduces stem competition for water resources, increasing forest resilience to the more arid conditions projected by RCP 2.6 and RCP 8.5 climate scenarios. Furthermore, the increase in mean annual temperature may favor the forest CO_2 sink capacity by enlarging the vegetative period and increasing the energy availability to photosynthesis.

Plot 3:

Table P3.1: Total carbon cumulated stock (Cs, in $tCO_2e \cdot ha^{-1}$) in plot 3 at year 2100 horizon. The different RCP scenarios are noted for each management regime, with the baseline and the No Management regime.

Management	RCP 0.0 Cs ($tCO_2e \cdot ha^{-1}$)	RCP 2.6 Cs ($tCO_2e \cdot ha^{-1}$)	RCP 8.5 Cs ($tCO_2e \cdot ha^{-1}$)
Ps02	263.4	247.6	364
Ps05	505.6	504.4	700
OMP	440	440.2	630.4
No Management	393.6	339.2	492

Ps05 is the forest management procedure that **maximizes in all cases the Cs**, with values ranging from **504.4 to 700 $tCO_2e \cdot ha^{-1}$** depending on the climate scenario (table P3.1). **RCP 2.6** is the climate scenario that supports lowest values of Cs in the plot for all management procedures. On the other hand, **RCP 8.5** is the climate scenario that presents higher Cs values, due the fertilizing effect of the increase in atmospheric CO_2 concentration in severe climate change projections. The **evenaged (Ps02)** management procedure is the management procedure with lowest Cs values in all climate scenarios, even **lower values than no management option**.

Table P3.2: Total carbon stock gain (ΔC_s, in $tCO_2e \cdot ha^{-1}$) in plot 3 during the 2015-2100 period. The different RCP scenarios are noted for each management regime, with the baseline and the No Management regime.

Management	RCP 0.0 ΔCs ($tCO_2e \cdot ha^{-1}$)	RCP 2.6 ΔCs ($tCO_2e \cdot ha^{-1}$)	RCP 8.5 ΔCs ($tCO_2e \cdot ha^{-1}$)
Ps02	-77.9	-93.6	22.2
Ps05	246.1	244.8	440
OMP	120	121	310.4
No Management	50.4	-4.1	148.2

The **forest management with highest values of ΔC_s during years 2015-2100 is the Ps05, with values reaching the 440 $tCO_2e \cdot ha^{-1}$** in the most productive climate scenario (Table P3.2). This is true for all climate change scenarios. **Lowest values of ΔC_s are**

found in the Ps02 evenaged forest management procedure. In the RCP 0.0 and RCP 2.6 those values are negative, indicating net CO_2 release to the atmosphere at the end of the management procedure. However, in a RCP 8.5 climate change scenario, even under the forest management procedure Ps02 plot 2 becomes a sink of carbon, with a ΔC_s value of 22.2 $tCO_2e \cdot ha^{-1}$. Considering climate change scenarios, **the climate change scenario that presents higher ΔC_s values is the RCP 8.5 for each management**, even in a non managed forest.

Table P3.3: Annual profitable wood extraction in $m^3 \cdot ha^{-1} \cdot year^{-1}$ for each management regime and for each climate change scenario. Wood quality has been differentiated between medium quality wood (14-35 cm) and high quality wood (35+ cm).

Management	Wood quality	RCP 0.0 ($m^3 \cdot ha^{-1} \cdot year^{-1}$)	RCP 2.6 ($m^3 \cdot ha^{-1} \cdot year^{-1}$)	RCP 8.5 ($m^3 \cdot ha^{-1} \cdot year^{-1}$)
Ps02	Medium (14-35 cm)	0.9	0.9	1.2
	High (35+ cm)	2.6	2.4	3.6
Ps05	Medium (14-35 cm)	5.3	5.3	6.9
	High (35+ cm)	0	0	0
OMP	Medium (14-35 cm)	5.1	5.1	7.1
	High (35+ cm)	0	0	0
No management	Medium (14-35 cm)	0	0	0
	High (35+ cm)	0	0	0

In plot 3 again the only forest management procedure that allows obtaining **high quality wood is the Ps02** (Table P3.3). However, the total amount of extracted wood is lesser than the other two forest management scenarios. The RCP 8.5 is the climate scenario that produces the largest amount of extractable wood for all forest management procedures. In management Ps02 a decrease in production of high quality wood is observed in RCP 2.6 climate scenario.

Table P3.4: Greenhouse gas emissions reduction compared to the baseline no management procedure (ΔC_{IFM}, in $tCO_2e \cdot ha^{-1}$) of the plot 3 for each management procedures and climate change scenarios.

Management	RCP 0.0 ΔC_{IFM} ($tCO_2e \cdot ha^{-1}$)	RCP 2.6 ΔC_{IFM} ($tCO_2e \cdot ha^{-1}$)	RCP 8.5 ΔC_{IFM} ($tCO_2e \cdot ha^{-1}$)
Ps02	-130.2	-91.7	-128
Ps05	112.1	165.2	208.1
OMP	46.4	101	138.4

The greenhouse gas emissions reduction compared to the baseline no management procedure (ΔC_{IFM}) takes **negative values for the Ps02 forest management procedure under all climate conditions** (Table P3.4). It indicates lower sink capacity of the forest compared to the baseline. Conversely, **Ps05 has a net positive ΔC_{IFM} that ranges between 112.1-208.1 $tCO_2e \cdot ha^{-1}$** depending on the climate change scenario considered. **OMP** presents intermediate but positive ΔC_{IFM} values (**46.6-138 $tCO_2e \cdot ha^{-1}$** depending on the forest management considered). Except for Ps02 forest management procedure, the highest ΔC_{IFM} values are obtained in **RCP 8.5** climate scenario.

Table P3.5: Yearly transpiration (Ec, in $mm.year^{-1}$) of the tree population for each management procedure and climate change scenario. Baseline no management procedure is already noted.

Management	RCP 0.0 Ec ($mm \cdot year^{-1}$)	RCP 2.6 Ec ($mm \cdot year^{-1}$)	RCP 8.5 Ec ($mm \cdot year^{-1}$)
Ps02	329	329	332
Ps05	275	280	288
OMP	261	268	279
No Management	356	352	348

In a no managed forest stand, tree transpiration (Ec) decreases at increasing aridity (Table P3.5). On the other hand, tree transpiration increases at increasing severity of climate change if forest managed is applied. However, Ec values in the plots under forest management do not reach No Management Ec values in any case. It means that management in all cases reduces stem competition for water resources, increasing forest

resilience to the more arid conditions projected by RCP 2.6 and RCP 8.5 climate scenarios. Furthermore, as discussed previously, climate change would increase the production of the forest analyzed if water limitation stands between the ranges modelized in this report.

General Results:

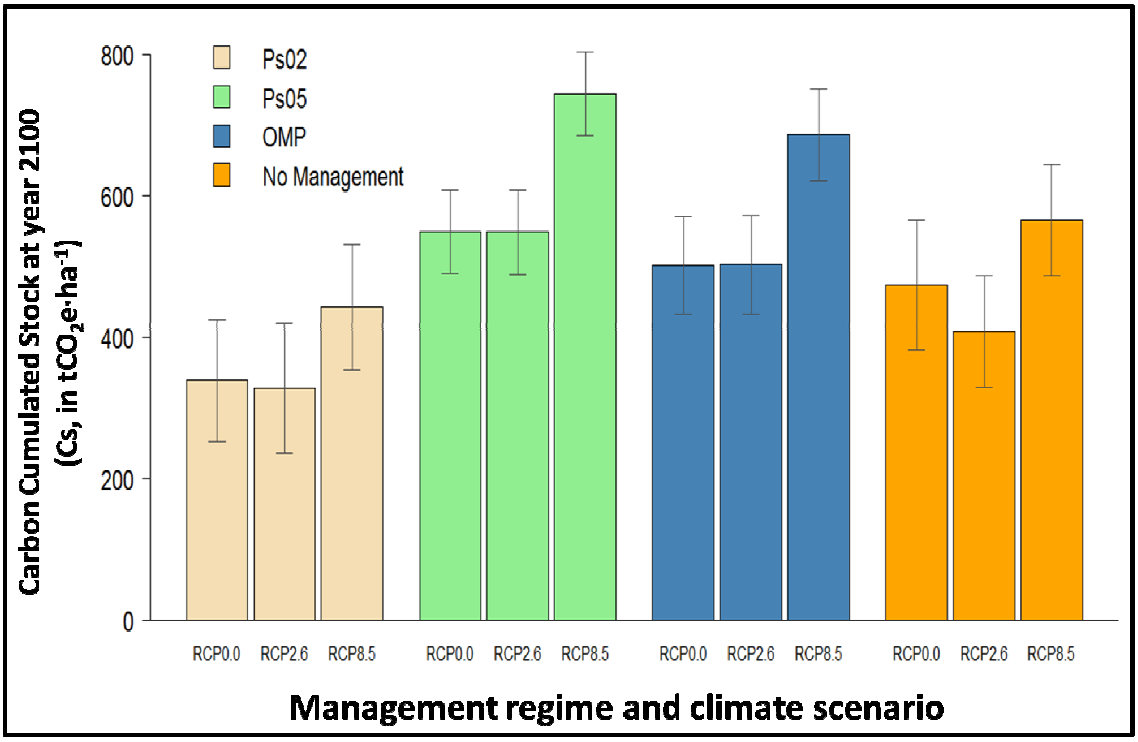


Figure 2: *Total carbon cumulated stock (Cs, in $tCO_2e \cdot ha^{-1}$) at year 2100. Bars represent mean values for all three forest stands analyzed and lines represent the standard deviation. Ps02 is noted in wheat color, Ps05 in green color, OMP in blue color and no management is noted in orange. The three climate scenarios have been considered separately.*

Ps05 is the management regime that maximizes cumulated carbon stocks in all cases, with mean values ranging **548-744 in $tCO_2e \cdot ha^{-1}$** (figure 2). On the other hand, **Ps02 is the management regime that minimizes cumulated carbon stocks** in all cases, acting as a source rather than a sink of CO_2 compared to the no management. Its Cs mean values ranges the **338-442 $tCO_2e \cdot ha^{-1}$**, depending on the climate scenario considered. According to our results, maintaining a young, dynamic population is crucial in order to

maximize the amount of CO_2 captured from the atmosphere. **However, younger stands produce lower quality wood. Tradeoffs between wood extraction quality and CO_2 sequestration capacity are one of our main results.** Our results also suggest that a severe climate change scenario is going to increase the sink capacity of the forest stands analyzed in all considered management procedures, as well as in no management regime. This is in accordance with Sabaté *et al.* (2002), who hypothesized that atmospheric CO_2 increment would increase forest production as a result of a fertilizing effect in photosynthetic machinery. Current observations, as those described by Keenan *et al.* (2013), are confirming this trend of increasing production when rising atmospheric CO_2 concentrations under no water availability limitation.

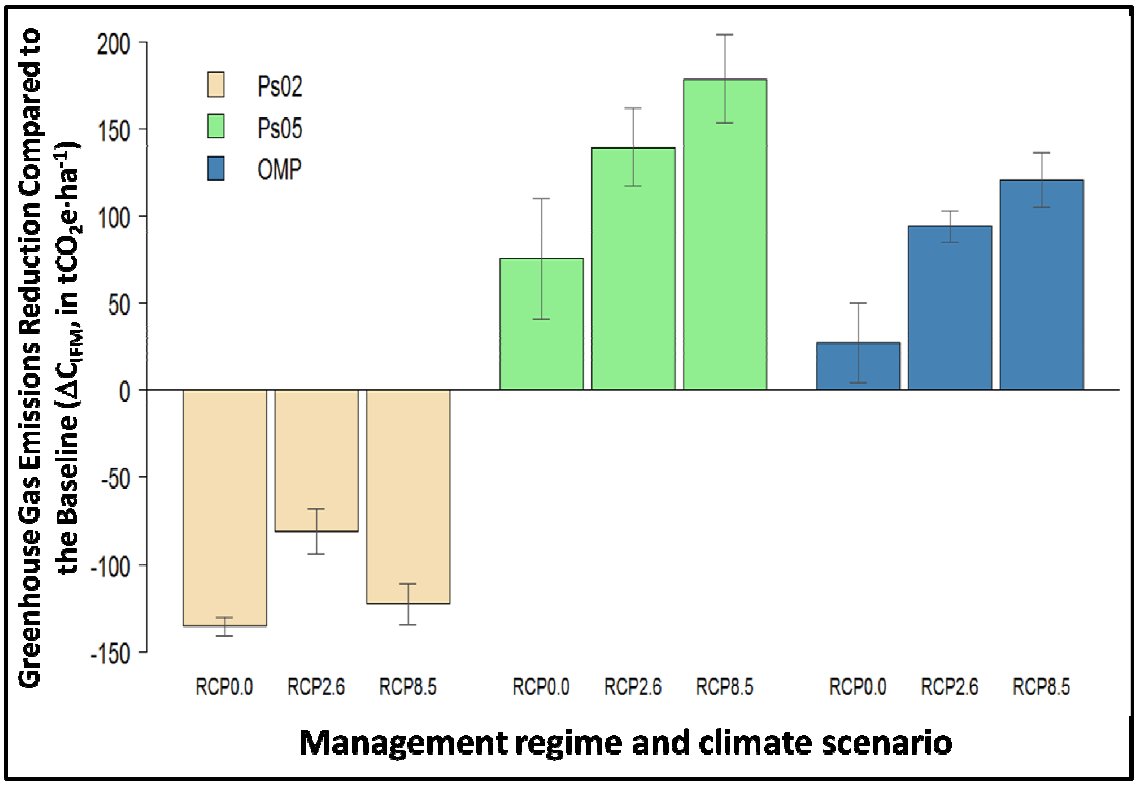


Figure 3: *Mean greenhouse gas emissions reduction compared to the baseline (ΔC_{IFM}, in $tCO_2e \cdot ha^{-1}$) for all three forest management regimes considered, and for each climate change scenario. Bars indicate mean values, arrows the SD of those mean values.*

In figure 3 mean greenhouse gas emissions reduction compared to the baseline no management stand (ΔC_{IFM}, in $tCO_2e \cdot ha^{-1}$) is shown for each management regime. Negative values in ΔC_{IFM} indicates a lesser carbon storage capacity than the baseline no management. **Ps02 presents negative ΔC_{IFM} values in each climate change scenario, mean values ranges from -135 to -81 $tCO_2e \cdot ha^{-1}$**. It indicates that Ps02 is not appropriated forest management in atmospheric CO^2 sequestration. **The forest management with higher ΔC_{IFM} values is the Ps05, which mean values ranges from 76 to 179 $tCO_2e \cdot ha^{-1}$ depending on the climate scenario.** It is interesting to note that **the more intense is climate change, the more efficient become both Ps02 and OMP in relation to ΔC_{IFM}**. Likely, it is due both to the lower competition between tree stems to water and energy resources in a managed stand, and a reduction in living biomass in the plot after each intervention, which decreases maintenance respiration of the managed forest stands compared to the baseline no management, where maintenance respiration is only reduced under tree mortality events.

In all cases, the 2020 horizon presents negative **ΔC_{IFM}** values, as the example shown in figure 1, because forest management had not been implemented yet enough to obtain positive values respect to the baseline unmanaged forest stand.

Our results also suggest **no water limitation in tree growth**. Water availability only **slightly limits tree growth in the no managed stand under climate change scenarios**. However, our results may not be extrapolated to drier areas, were water availability has been demonstrate the main constrain for tree growth. **The increase in Ec of managed stands indicates that there is a shift from slight water constraint under no managed stands to an energy availability limitation in managed stands**.

That is the reason why, in climate change scenarios, the total amount of water transpired by tree population increases if managed.

Conclusions:

The **most efficient forest management** procedure in greenhouse gas emissions reduction compared to the baseline no management procedure (ΔC_{IFM}) during the 2015-2100 period is the **Pn05** in all climate change scenarios. Its values range from **76 to 179 $tCO_2e \cdot ha^{-1}$** depending on the climate change scenario considered. However, an **inefficient management**, as **Ps02**, with ΔC_{IFM} values ranging the **-135 to -81 $tCO_2e \cdot ha^{-1}$** may reduce stand carbon sink capacity compared to the unmanaged stand.

Under **RCP 8.5 climate change conditions**, projections show an i**ncrease of carbon stock gain (ΔC_s)** during years 2015-2100 compared to the RCP 0.0 for all forest management procedures **of about 30-90%**.

Only **Ps02 forest management regime generates high quality wood**. It generates **2.4-5 $m^3 \cdot ha^{-1} \cdot year^{-1}$** of high quality wood depending on the climate change scenario and the forest stand considered. **OMP and Ps05 produce only medium quality wood**.

The projected increase in atmospheric CO_2 concentration, as well as the increase in mean annual temperature, **is likely going to increase forest production** in the La Muntanya d'Alinyà Mountains.

A **properly management procedure may reduce the competition for water resources** in the forest plots analyzed. It is going to **increase their resilience to drought disturbances**.

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